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DETERMINATION OF ELEVATED-TEMPERATURE FATIGUE DATA ON REFRACTORY ALLOYS IN ULTRA-HIGH VACUUM

SEVENTH QUARTERLY REPORT

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LEWIS RESEARCH CENTER

UNDER CONTRACT NAS 3-6010

TRW EQUIPMENT LABORATORIES

CLEVELAND, OHIO

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Seventh Quarterly Report

for

1 January 1966 to 1 April 1966

DETERMINATION OF ELEVATED-TEMPERATURE FATIGUE DATA ON REFRACTORY ALLOYS IN ULTRA-HIGH VACUUM

Prepared by:

C. R. Honeycutt and J. C. Sawyer

Approved by:

E. A. Steigerwald

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS 3-6010

TECHNICAL MANAGEMENT

Paul E. Moorhead
Space Power Systems Division
NASA - Lewis Research Center

April 15, 1966

TRW EQUIPMENT LABORATORIES
TRW Inc.
23555 Euclid Avenue
Cleveland, Ohio 44117

FOREWORD

The work described herein is being performed by TRW Inc. under the sponsorship of the National Aeronautics and Space Administration under Contract NAS 3-6010. The purpose of this study is to obtain fatigue life data on refractory metal alloys for use in designing space power systems.

The program is administered for TRW Inc. by E. A. Steigerwald, Program Manager, C. R. Honeycutt and J. C. Sawyer are the Principal Investigators. The NASA technical director is P. E. Moorhead.

Prepared by J. C. Sawyer
J. C. Sawyer
Sr. Research Metallurgist

Prepared by C. R. Honeycutt
C. R. Honeycutt
Research Metallurgist

Approved by E. A. Steigerwald
E. A. Steigerwald
Research Supervisor

TABLE OF CONTENTS

I INTRODUCTION

The purpose of this investigation is to generate fatigue data for refractory alloys at elevated temperatures in ultra-high vacuum environments. The ultimate objective is to determine whether fatigue life or creep is the limiting design parameter in turbine applications involving space-power systems.

During this report period additional notched fatigue tests were conducted at 2000°F (1093°C) on TZC alloy. From the results of these tests S/N curves have been defined for "A" ratios* of ∞ and 0.67. Smooth specimens of TZC have been tested at an "A" ratio of approximately 0.20 and a static load of 20 Ksi ($1.38 \times 10^9 N/m^2$). Limited creep data have also been obtained from these smooth-specimen fatigue tests.

Specimens of TZM with various notch configurations are being evaluated under dynamic load conditions. The results obtained to date indicate that the peak stress required for fatigue of smooth specimens is significantly greater than that required for notched specimens. At present the specific reason for this difference is not known but the effect of localized self-heating may be a contributing factor.

Further study has been undertaken to assess the requirements necessary to cause fatigue of smooth TZC specimens at an "A" ratio of ∞. The results of tests conducted to determine the requirements for producing fatigue in smooth specimens show that with the vibrational drive available at 20 kHz, the magnitude of the dynamic stress delivered to the specimen is limited by the large amount of energy converted to heat through internal damping.

II MATERIALS

The molybdenum-base alloys TZM and TZC are the materials being investigated in the test program. The specific material form, heat numbers, and compositions are presented in Table 1. The TZM alloy has been employed primarily as a working material to define the effects of notch geometry and to optimize the design of the load train assembly. The TZC alloy has been evaluated as bar stock and plate material from two heats (M-89 and M-91). The processing history of the TZC plate, described in the Fifth Quarterly Report, CR 54775, was significantly different for each of the heats being evaluated. With the exception of one test which was performed on the stress-relieved material, the TZC specimens were annealed at 3092°F (1700°C) for one hour in vacuum prior to testing. Tests on the TZM were conducted in both the stress-relieved and recrystallized conditions.

* Ratio of dynamic stress to mean stress.

TABLE I

CHEMICAL COMPOSITION OF ALLOYS TESTED

Material	Form	Vendor	Heat	Composition - Weight %				Condition
				Mo	Zr	Ti	C	
TZM	1/2" dia. Bar	Climax	7463	Bal.	0.08	0.48	0.016	Stress Relieve, 1 hour at 1232°C
TZM	1/2" dia. Bar	Climax	7468	Bal.	0.09	0.50	0.022	Stress Relieve, 1/2 hour at 1232°C
TZC	1/2" dia. Bar	Climax	4263	Bal.	0.38	1.24	0.10	Stress Relieve, 1/2 hour at 1240°C
TZC	1/2" dia. Bar	Climax	4230-2	Bal.	0.29	1.35	0.089	Stress Relieve, 1/2 hour at 1315°C or anneal 1 hour at 1700°C
TZC	0.60" Plate	G. E.	M-89	Bal.	0.20	1.45	0.13	Anneal at TRW 1700°C, 1 Hour ASTM Grain Size 1 to 4
TZC	0.60" Plate	G. E.	M-91	Bal.	0.18	1.25	0.14	Anneal at TRW 1700°C, 1 Hour ASTM Grain Size 4 to 6

III PROCEDURE

The program plan involves conducting fatigue tests at approximately 20 kHz on both smooth and notched specimens. Since sufficient stress could not be generated on the smooth specimens to consistently produce a failure at a test temperature of 2000°F (1093°C), considerable effort has been devoted to varying the load train design so that increased ultrasonic drive could be developed.

The test specimen geometries, shown in Figures 1 and 2, are based on the calculations of Neppiras.* Both utilize the dumb-bell type geometry with a gage-length diameter of 1/4 inch. The test method involves mechanically mounting the specimen to the drive train, adjusting the capacitive vibration pick-up, making preliminary checks to insure the system is in resonance, and pumping the unit to a vacuum better than 1×10^{-8} Torr at room temperature. Testing is performed at this vacuum except during heating which is controlled at such a rate that the pressure never exceeds 1×10^{-6} Torr.

A W-3%Re/W-25%Re thermocouple placed approximately 1/8 inch from the surface at the specimen midpoint is used for temperature measurement. Due to breakage produced by the vibration, the thermocouple cannot be attached directly to the specimen. The temperature is stabilized for approximately two hours prior to the application of the cyclic load.

As a result of the application of the high frequency cyclic load, heating of the fatigue specimen takes place. For a given material the degree of heating is dependent upon the power applied to the system. In determining the S/N curve, the ambient test temperature; i.e., the temperature recorded by the thermocouple is set at a fixed value for each test. At the high stress levels where significant heating of the specimen occurred, the test time was sufficiently short so that a readjustment of the furnace temperature to compensate for the self-heating could not be accomplished. At the low values of applied dynamic stress, the temperature increase was very slight and no adjustment of the furnace temperature was usually necessary. Although the data are presented for constant values of the ambient temperature, the actual specimen temperature was also recorded in cases where the test duration was sufficient to allow time for accurate readings. The temperature increase due to self-heating was obtained with an L-N optical pyrometer by measuring the difference in specimen brightness temperature before and after the application of the cyclic load.

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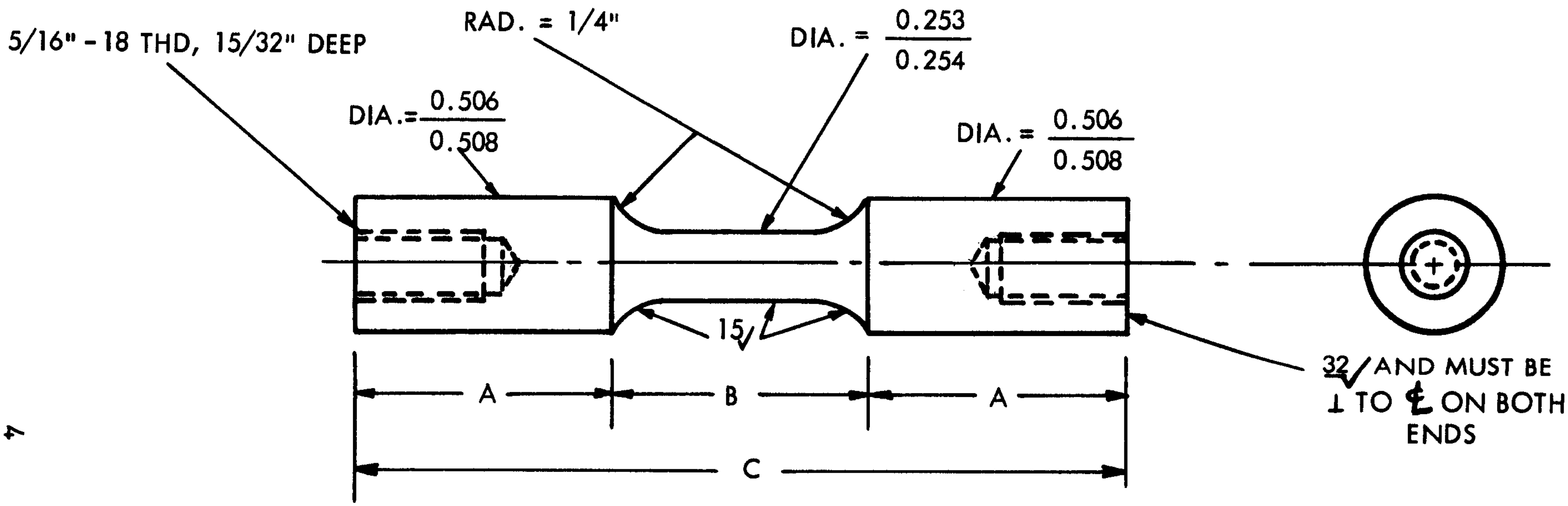
* E. A. Neppiras, "Techniques and Equipment for Fatigue Testing at Very High Frequencies," Proc. ASTM, 59, 691-709, (1959).



ALL DIAMETER & THD. ENDS MUST BE CONCENTRIC ± 0.002 T.I.R.
USE MINIMUM RELIEF ON THD. ENDS.

	A (IN.)	B (IN.)
TZC	0.980	0.980
TZM	1.155	1.155

FIGURE 1 DUMB-BELL TYPE SMOOTH SPECIMEN GEOMETRY

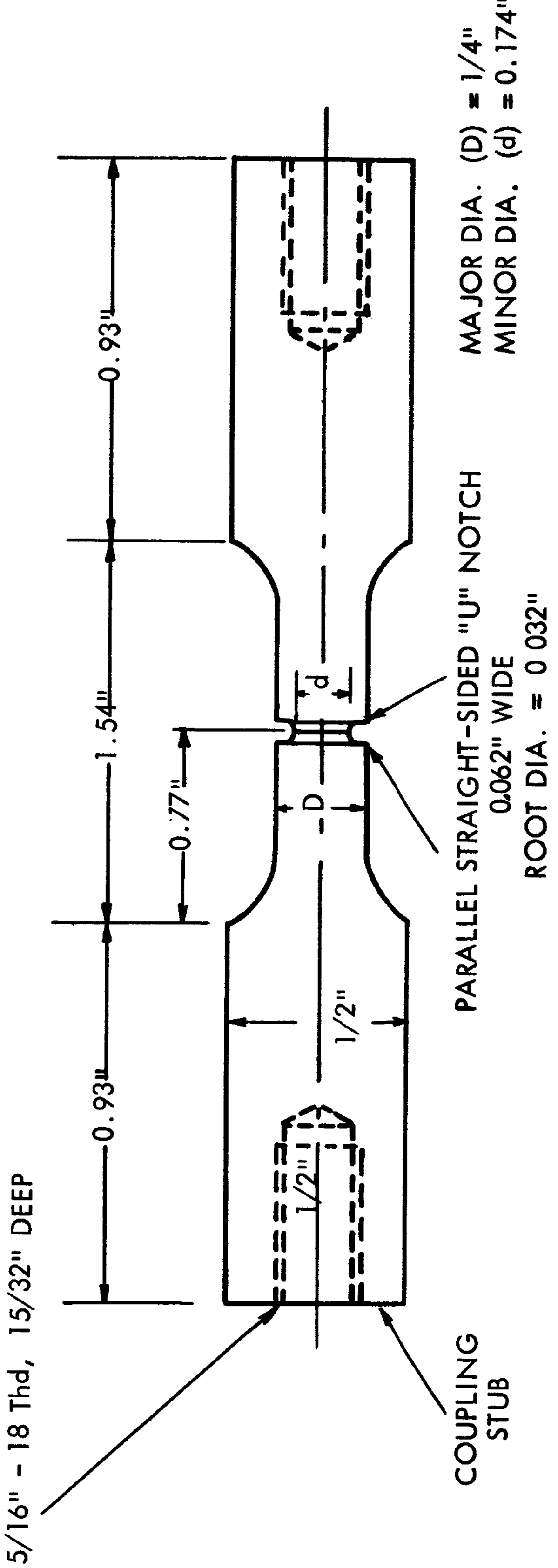


FIGURE 2 GEOMETRY OF NOTCH FATIGUE SPECIMEN

The applied dynamic stress produced by the ultrasonic vibration was determined from displacement measurements made directly on the specimen with a cathetometer. In the dumb-bell specimens two reference points were selected approximately equidistant from the specimen midpoint and the displacements at these points were determined by averaging 10 readings. The variation in these readings was approximately ±50μ-in. The displacement along the specimen was assumed to follow the sinosoidal relationship:

$$\delta_x = \delta_o \sin \frac{2\pi x}{\lambda} \qquad (1)$$

where: $2\delta x$ is the total measured displacement at a distance x from the specimen midpoint,

δ_o is the maximum amplitude, and

λ is the resonant wave length.

The maximum strain (ϵ max) at the midpoint of the dumb-bell type specimen can then be determined from the equation:

$$\epsilon_{max} = \frac{2\pi\, \delta_o}{\lambda} \qquad (2)$$

and the dynamic stress (σ) is the product of the strain and the elastic modulus at the particular test temperature

$$\sigma_{max} = (\epsilon\ max)\ \ (E) \qquad (3)$$

When the notch specimen was employed, the calculations of stress based on the displacement measurements taken on the major diameter must be increased by the area ratio and the theoretical stress concentration factor. On this basis the stress in the notch specimen was calculated from the following relation:

$$\sigma = \left(\frac{D}{d}\right)^2 K_T \left(\frac{2\pi}{\lambda}\, \delta_o E\right) \qquad (4)$$

where: K_T is the theoretical stress concentration factor,

D is the major specimen diameter, and

d is the minor specimen diameter.

All the tests were conducted in the 18.0 to 21.0 kHz range. Cracking of the test specimen was accompanied by a significant decrease in the resonant frequency. Although the end point was defined as the point when this rapid shift in resonance occurred the test was continued until the desired amplitude could no longer be obtained. This condition usually resulted in propagating the fatigue crack through approximately one-half the specimen cross-section.

Drive Train Design

During this quarter emphasis was placed on finalizing the design of the drive train and determining the magnitude of the dynamic stress which was possible with the existing equipment.

The dynamic drive system is based upon a ferroelectric element providing a longitudinal displacement to a resonant drive train with the consequent development of a standing displacement in the drive train and specimen. To determine the stress in such a system requires a knowledge of the modulus of the material at operating temperatures and the wave length of the displacement. Since TZC is the principal material of interest, tests have been conducted to establish that the modulus in this material at 20 kHz and 2000°F (1093°C) is 3.6×10^6psi (24.8×10^{11}N/m^2) and the wavelength under these same conditions is 9.80 inches. From equations 2 and 3 the displacement amplitude required for a nodal stress of 45 Ksi* at 2000°F (1093°C) with TZC is 1.95×10^{-3} inches. Thus, a TZC bar at 2000°F (1093°C) will be resonant at 20 kHz if its length is a multiple of 4.90 inches ($\lambda/2$) and the longitudinal stress will be 45 Ksi (3.1×10^8N/m^2) at the node if the maximum displacement amplitude is 0.00195 inches.

The drive element selected for this program was a lead-zirconate-titanate (PZT) cylinder containing a silver coating on the inner and outer surfaces. The dimensions of this element shown in Figure 3, are such that when a sinusoidal voltage is applied to the electrodes, the element elongates and contracts at the frequency of the applied voltage. While the displacement amplitude is a function of the applied voltage, the limitation of crystal heating resulted in the system being designed for an input power of about 200 watts at 250-300 volts. When this input voltage is applied to the crystal, the displacement amplitude is approximately 7.5×10^{-5} inches. To increase the displacement amplitude of the driving element mechanical amplifiers are used. The general design of these amplifiers, shown in Figure 4, employs an overall length which is a multiple of a half wave with the transformation step located at a displacement node. Titanium and TZM were selected for the mechanical amplifiers because of their low energy losses and high strength. With an amplifier of this design the gain in displacement amplitude is related to $(D/d)^2$ where D is the larger diameter and d the smaller diameter. In going from a 2-inch diameter crystal to a 1/2-inch diameter rod, to which the specimen is attached, a theoretical gain of 16 should be obtained, which when combined with the gain afforded by the dumbell specimen design should provide enough amplification so that the desired displacement of 1.95×10^{-3} inches could be obtained.

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* The value of 45 Ksi was initially selected as a target stress for the equipment design.

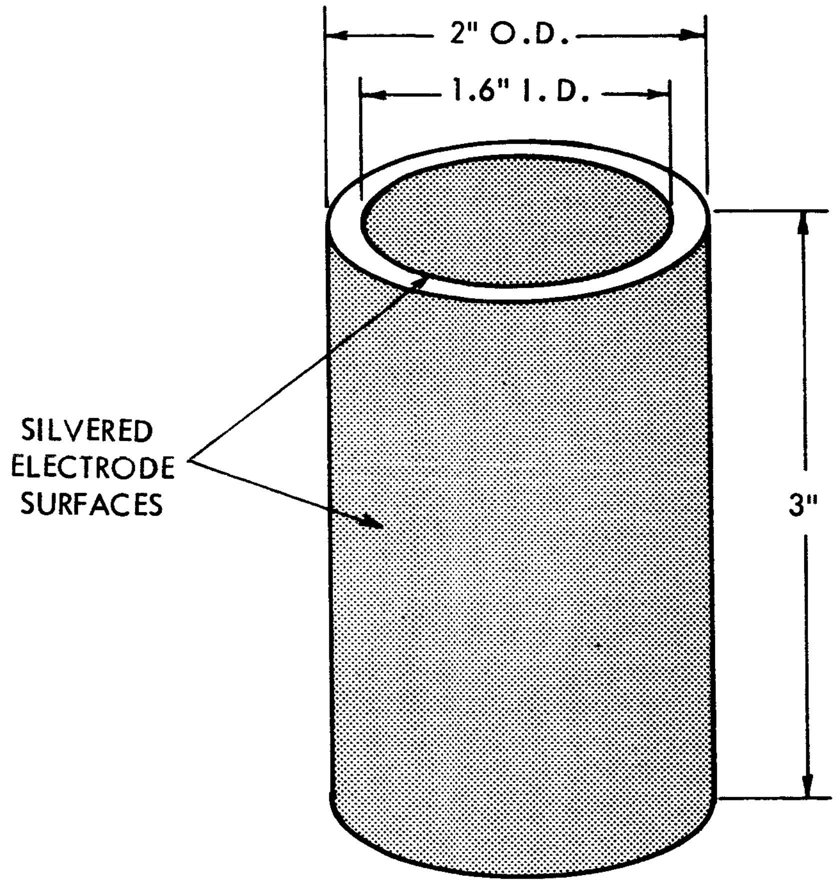

FIGURE 3 LEAD-ZIRCONATE-TITANITE (PZT) CRYSTAL HAVING A LONGITUDINAL RESONANT FREQUENCY OF APPROXIMATELY 20 kHz

1572A

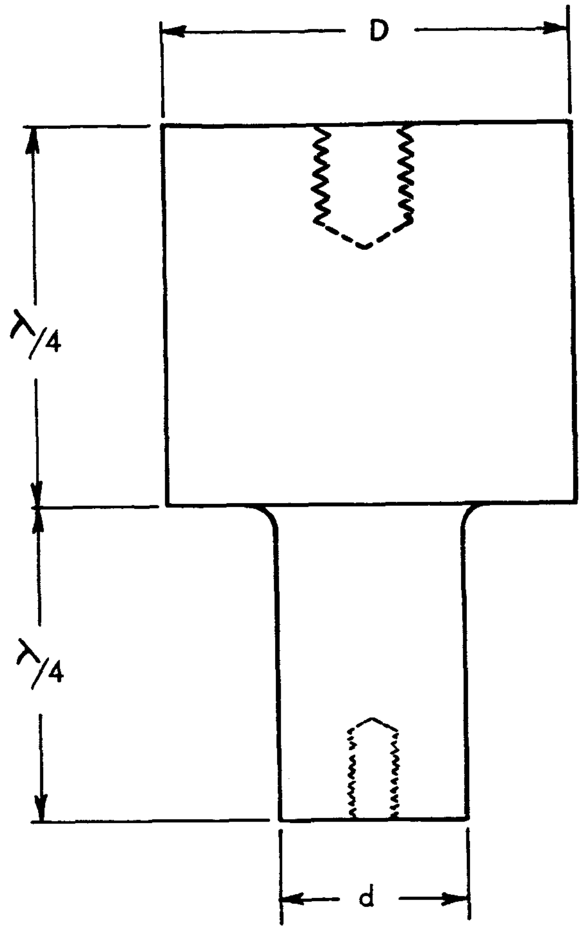

FIGURE 4 DESIGN OF MECHANICAL AMPLIFIER USED IN DRIVE TRAIN

In actual practice, with a load train and specimen as shown in Figure 5, a maximum displacement of only 1 to 1.25 x 10^{-3} in. could be obtained when the specimen was at temperatures above 1500°F (815°C). Various design alternations have been evaluated in an attempt to increase the resultant amplification, with little improvement in results, during the elevated temperature tests.

During this quarter, a series of tests were run with a 1 Kw Blackstone* drive unit to determine whether the joints between horns, located at the displacement antinodes, significantly contributed to a loss of displacement in the drive train. The arrangement for this test is shown in Figure 6. The magnetostrictive vibrator was coupled to a titanium mechanical amplifier which in turn was coupled to a resonant TZM bar. The drive train was long enough so that the end was located slightly below the center of the furnace in the vacuum chamber. A vacuum seal was produced by resting the step of the titanium horn on a rubber gasket and the system length was designed to produce a resonance at 20.6 kHz with a mechanical amplification of 2.25X. The titanium horn was attached to the 1-1/2 inch diameter output stub of the generator with a 1/2-20 steel stud and the TZM bar was attached to the titanium horn with a 3/8-24 steel stud. Since the end of the TZM bar located in the furnace was a displacement antinode, measurements of the motion were made at this point with a cathetometer and the results are summarized in Table II. At room temperature relatively high stresses could be developed, but on heating the TZM bar to 2000°F (1093°C), the maximum calculated stress decreased to approximately 15 Ksi (1.03 x $10^8 N/m^2$). In most cases, at room temperature it was necessary to operate the generator at a fraction of its maximum power and extrapolate the results to maximum drive, because fatigue of the drive train would result. The first two tests given in Table II show that the mechanical joint between the titanium amplifier and the TZM bar does not cause attenuation of the displacement. Test No. 3 indicates that when the drive train is mounted in the vacuum unit, using the horn step and a 1/16 inch rubber gasket, some loss of displacement occurs. Heating of the lower end of the TZM bar (about 6 inches) to 2000°F (1093°C) does cause a decrease in frequency and a significant loss of displacement. Since this decrease in displacement might be due in part to the titanium mechanical amplifier operating at a frequency below its design, the TZM bar was shortened to increase the operating frequency and move the displacement node of the mechanical amplifier. As shown by the data, the maximum stress developed at this higher frequency decreased despite the fact that the mechanical amplifier was operating more efficiently. This result indicated that the primary cause of displacement loss on heating was due to increased mechanical damping of the TZM alloy.

In the test just described, the TZM bar attached to the titanium horn was 1 inch diameter. To provide a second mechanical amplifier, the bar was machined to 1/4 inch diameter as shown in Figure 7 to produce a theoretical gain of 16. The results given in Table III show that at room temperature the maximum nodal stress in the 1/4 inch diameter section, extrapolated from

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* Blackstone Corporation, Sheffield, Pennsylvania

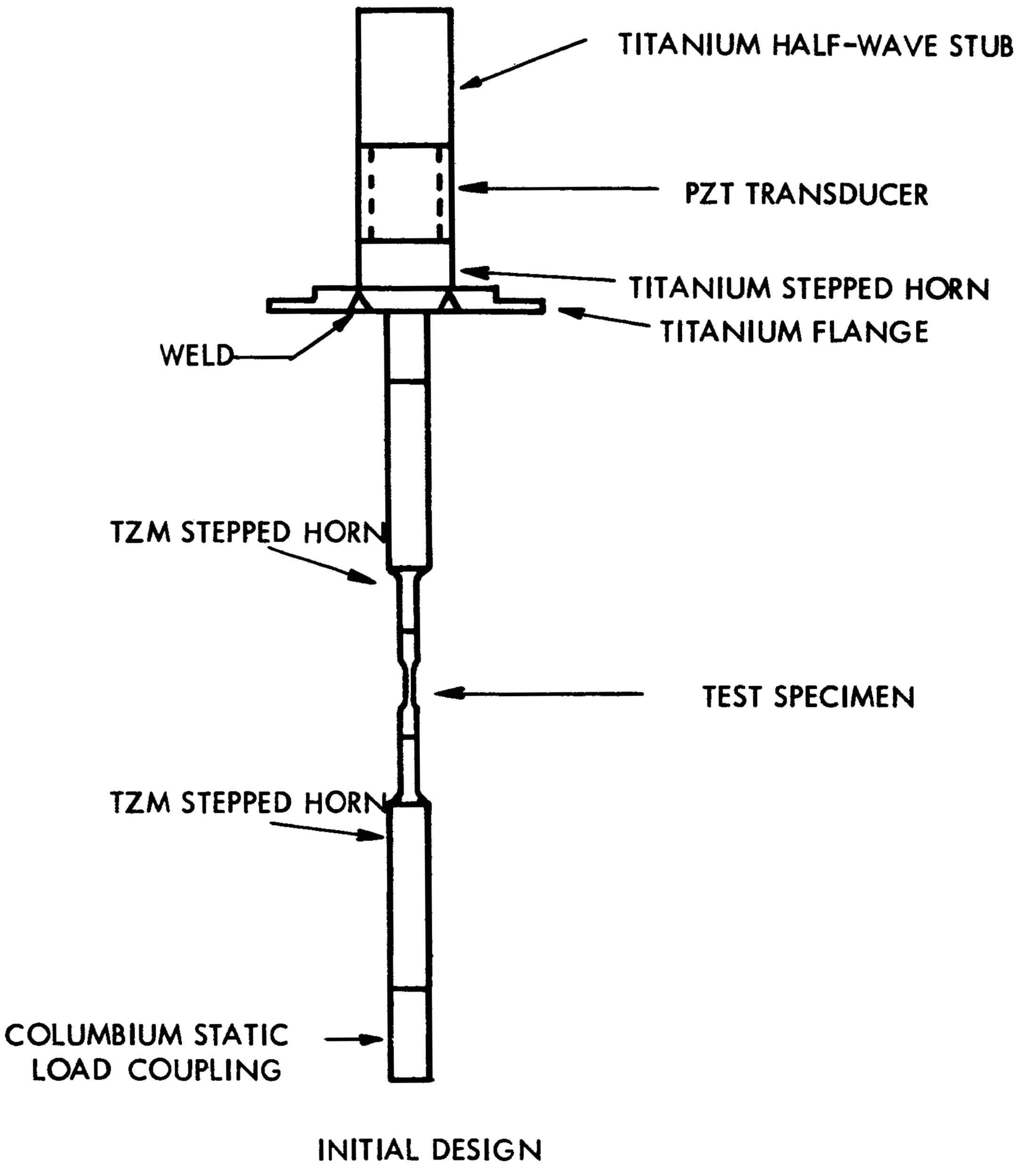


FIGURE 5 DESIGN OF ULTRASONIC DRIVE TRAIN

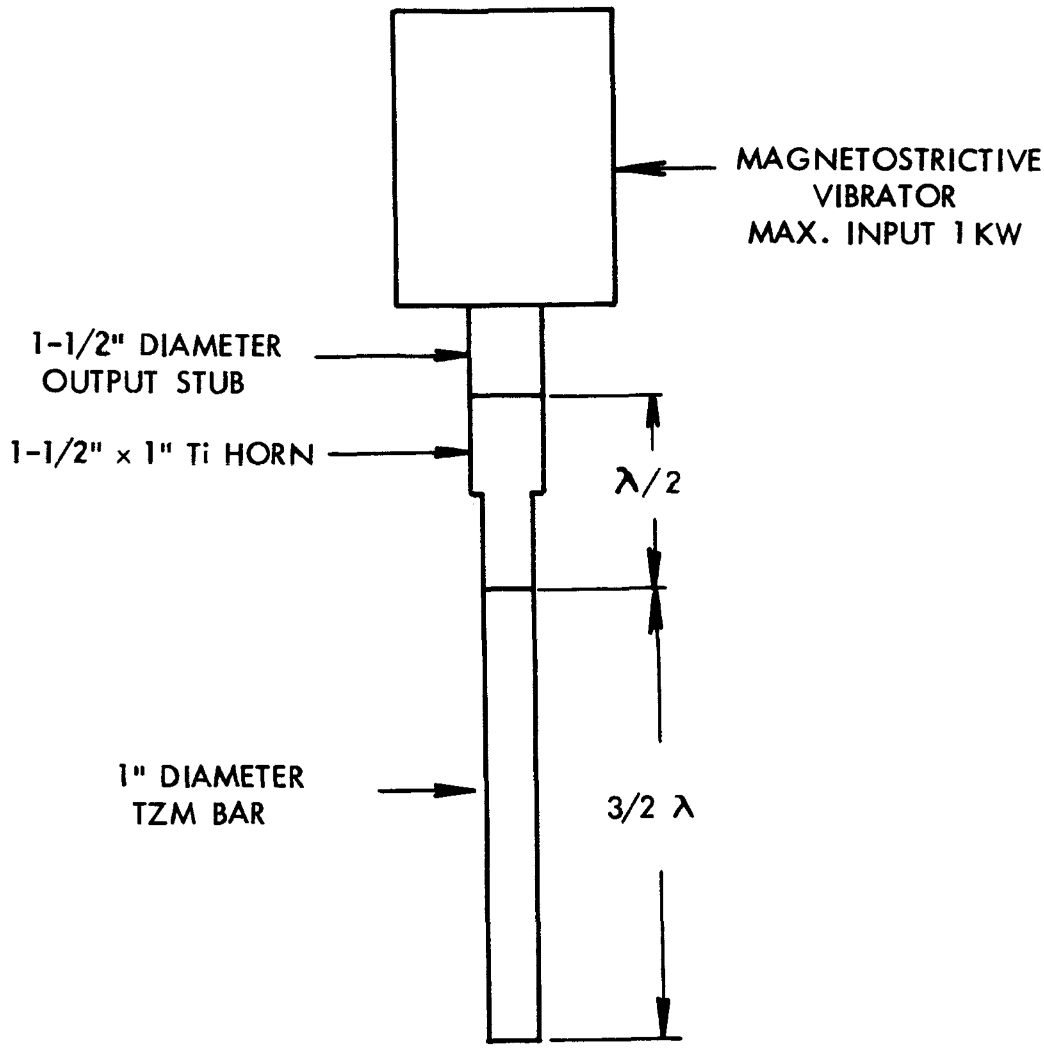


FIGURE 6 DESIGN OF MAGNETOSTRICTIVE DRIVE TRAIN WITH 1" DIAMETER BAR

TABLE II

Effect of Joints on Drive Train Efficiency

Test No.	Length of 1" Dia. TZM Bar	Temp. of Bar, °F	Freq. kHz	Stress-KSI (Max.Drive)	Remarks
1	Driver & Horn Only	-	20.6	60*	(Computed from maximum displacement)
2	16.25	RT	20.6	60*	(Unmounted)
3	16.25	RT	20.6	48*	Specimen mounted in chamber
4	16.25	2000	19.5	20*	
5	15.38	2000	20.5	9	TZM bar shortened from test No. 4 to increase drive frequency
6	10.83	RT	20.6	54*	
7	10.83	2000	19.5	15	
8	10.45	2000	20.1	14	

* Values extrapolated from measurements at lower power.

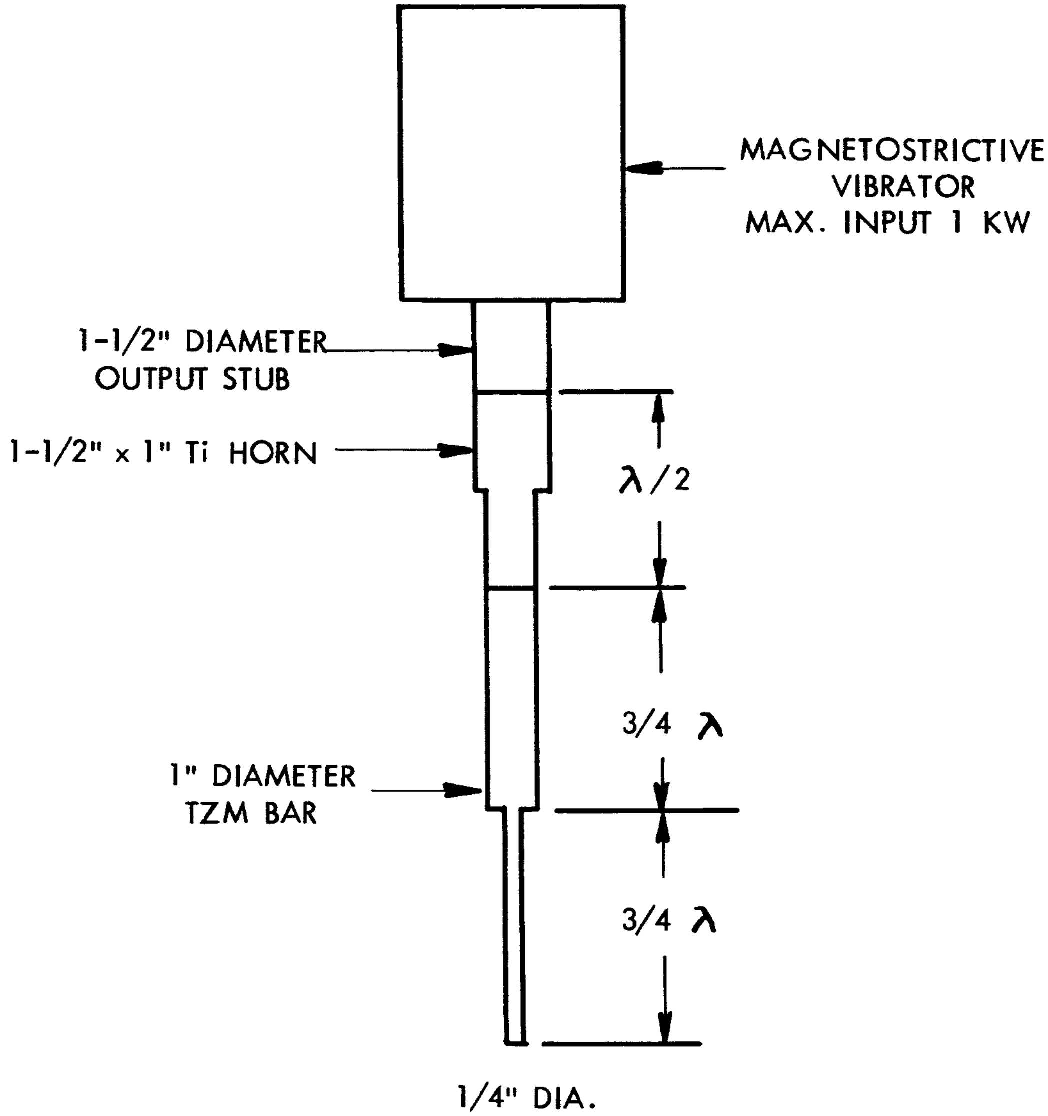


FIGURE 7 DESIGN OF MAGNETOSTRICTIVE DRIVE TRAIN WITH 1/4" DIAMETER BAR

TABLE III

Effect of Temperature and Step Location on Drive-Train Efficiency

Train Configuration	Temperature °F	Frequency kHz	Stress - Ksi Maximum Drive
TZM - 1" Diameter x 3/2 λ	RT	20.6	48*
	2000	19.5	18*
TZM - 1" Diameter x 3/4 λ plus 1/4" Diameter x 3/4 λ	RT	21.3	250*
	1200	20.6	24
TZM - 1" Diameter x 1/4 λ plus 1/4" Diameter x 5/4 λ	RT	21.5	250*
	1420	20.8	23
	2000	20.3	17

* At the specific conditions full power could not be used or else horn fracture would occur. The indicated values were obtained by measurements at lower power levels extrapolated linearly to the maximum drive.

reduced power data, was 250 Ksi ($1.72 \times 10^9 N/m^2$) indicating that the added mechanical amplifier was providing a gain of at least 5X. With continued operation at room temperature at reduced power, the 1/4 inch diameter section self-heated to approximately 1200°F (649°C). During heating, the nodal stress decreased even though the input power was increased until at full power the maximum stress in the 1/4 inch section was only 24 Ksi ($1.65 \times 10^8 N/m^2$). To determine whether the position of the horn step relative to the furnace hot zone influenced amplification, a second TZM bar was employed with the step of the mechanical amplifier placed above the hot zone. At room temperature this design provided no variation in performance when compared with the design shown in Figure 7. On self-heating to 1420°F (771°C) the maximum stress developed at full power was 23 Ksi ($1.58 \times 10^8 N/m^2$) which was also comparable to the previous test. When supplemental heat was supplied from the furnace element to bring the temperature to 2000°F (1093°C) the maximum stress decreased further to 17 Ksi ($1.70 \times 10^8 N/m^2$).

These results show that if the drive train is kept at room temperature, the maximum stress which can be developed with the 1 Kw magnetostrictive driver is well in excess of that required to fracture TZC. However, due to the increase in temperature due to damping a condition of high stress cannot be maintained without external cooling. Any heating of the drive train caused a rapid increase in the amount of vibrational energy absorbed and a corresponding increase in temperature. Power measurements show that at room temperature approximately 10-15 watts is needed to produce a stress of 25 Ksi ($1.72 \times 10^8 N/m^2$) indicating that the drive train efficiency is high; however, at 2000°F (1093°C) 1000 watts will not produce this same stress indicating an efficiency of less than 2%. Higher efficiencies could be realized if the operating frequency were decreased, since internal damping is frequency dependent with less energy being expended as heat at the lower frequencies.

These results indicate that the inability to produce the required stress in TZC at elevated temperatures and at 20 kHz is not the result of losses in the mechanical joints but is primarily due to the magnitude of the internal damping that occurs at high temperatures.

Fatigue Tests

Tests of notched specimens were conducted to develop S/N curves for TZC (Heat M-91) annealed one hour at 3092°F (1700°C). These data obtained at 2000°F (1093°C) for "A" ratios of ∞ and 0.67 are given in Table IV and plotted in Figure 8. The fatigue life is extremely sensitive to stress and does not exhibit a pronounced endurance limit at the elevated test temperature.

Using the data from Figure 8, the Goodman diagram shown in Figure 9, was constructed. Because of the time dependent trend of the fatigue data, two curves have been presented. One represents fatigue at times of less than one hour while the other is for fatigue in approximately 1000 hours. The values plotted on the abscissa at zero dynamic stress are the ultimate and

TABLE IV

Summary of Notched Fatigue Tests on TZC Plate (Heat M-91), Recrystallized 3092°F (1700°C), Ambient Test Temperature 2000°F (1093°C), Vacuum Environment <1 x 10^{-7} Torr

Specimen	Static Stress (Ksi, 6.89 x $10^6 N/m^2$)	A-ratio	Peak Total Stress (Ksi, 6.89 x $10^6 N/m^2$)	Failure Time (Hours)	No. of Cycles to Failure	Temperature Increase °F
17	1.33	∞	16.6	>143	>1 x 10^{10}	0
17	1.33	∞	21.5	0.60	4.1 x 10^7	-
18	19.6	0.67	32.6	0.10	6.8 x 10^6	-
20	1.33	∞	19.8	0.37	2.6 x 10^7	-
22	15.3	0.56	23.9	>4.5	>3.1 x 10^8	10
23	10.9	0.65	18.0	5.9	4.1 x 10^8	-
24	11.5	0.78	20.4	68.0	4.7 x 10^9	8
25	15.3	0.65	25.3	7.4	5.1 x 10^8	22
26	15.3	0.62	24.7	>0.80	>5.5 x 10^7	0
27	1.33	∞	18.2	0.67	4.6 x 10^7	24
28	1.33	∞	18.8	0.73	5.0 x 10^7	18
29	1.33	∞	16.1	10.0	6.8 x 10^8	39

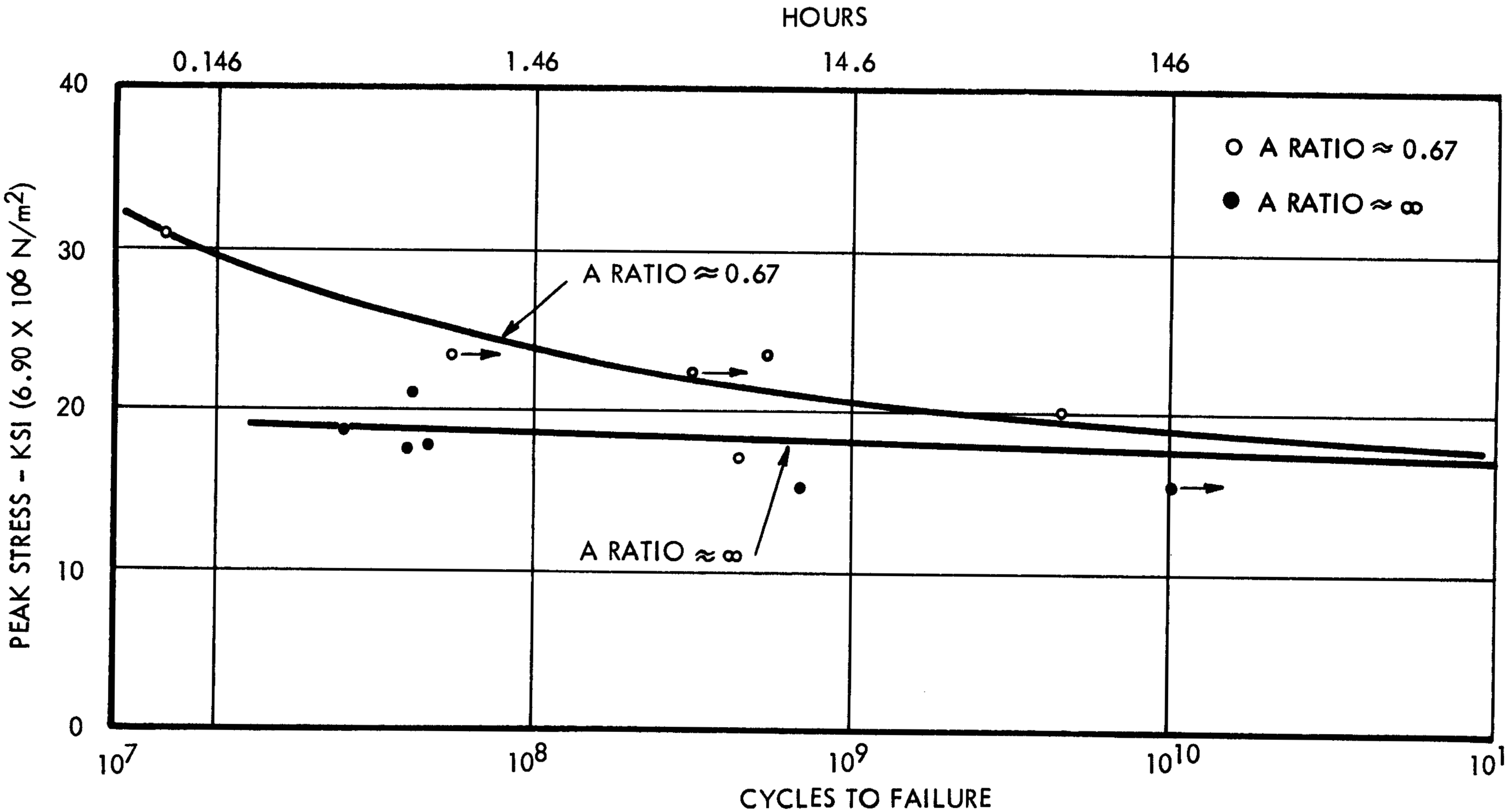


FIGURE 8 FATIGUE CURVES FOR NOTCHED SPECIMENS (K_T = 1.83) TZC, HEAT M-91, RECRYSTALLIZED AT 3092°F (1700°C) TESTED AT AN AMBIENT TEMPERATURE OF 2000°F (1093°C) IN A VACUUM ENVIRONMENT, TEST FREQUENCY 20kHz

15734

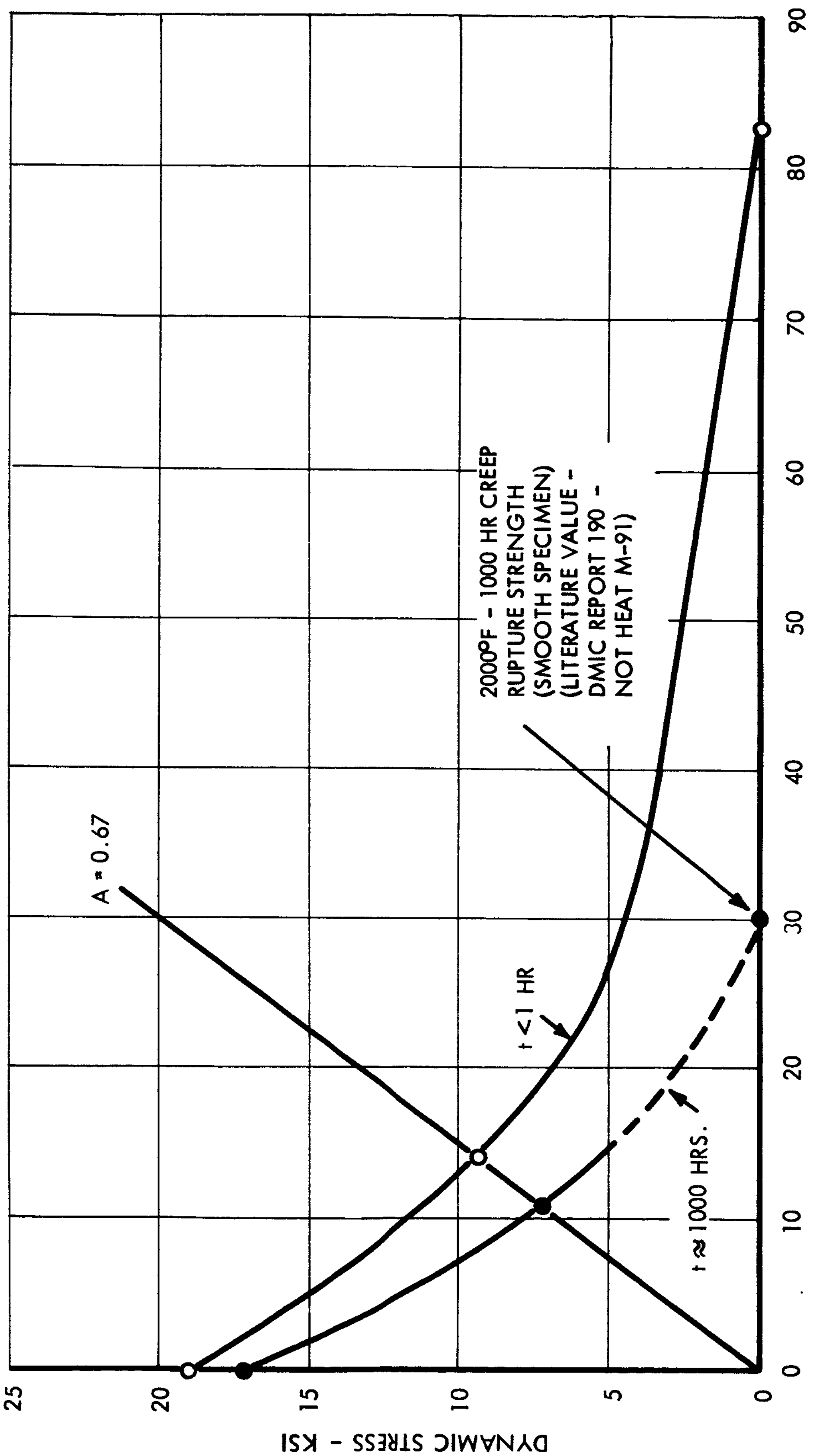


FIGURE 9 GOODMAN DIAGRAM FOR 20KC (20kHz) FATIGUE STRENGTH OF NOTCHED TZC (HEAT M-91) ANNEALED 1 HOUR 1700°C (3092°F), TESTED AT 2000°F (1093°C)

1302A

1000 hour creep rupture strengths of annealed TZC at 2000°F (1093°C). The ultimate strength of 80.3 Ksi ($5.52 \times 10^8 N/m^2$) was obtained from an annealed specimen of TZC (Heat M-91) having the same notch configuration as used in the fatigue tests. Since creep-rupture data for annealed TZC from Heat M-91 were not available, a value of 30 Ksi ($2.07 \times 10^8 N/m^2$) was estimated from the literature.* The unusual feature of the Goodman diagram obtained from the notch TZC tests is that the curves show a greater dependency on static stress than usually exhibited.

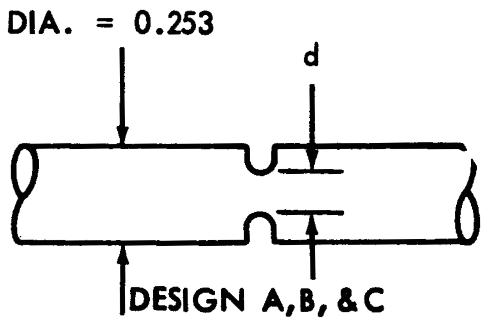
In the Sixth Fatigue Quarterly Report (NASA CR-54916) data were presented for Armco iron tested at room temperature which indicated a reasonably good correlation between results obtained on smooth and notch specimens. Isolated experiments, however, on TZC and TZM at elevated temperatures indicated that the fatigue strength of smooth specimens of annealed TZC and TZM were considerably greater than predicted from notched specimen results. To study the cause for this apparent difference, specimens of TZM (Heat 7468) having different notch configurations (see Figure 10) were annealed for one hour at 2850°F (1566°C) and tested at an ambient temperature of 2000°F (1093°C). The results, obtained to date (Table V), show that the smooth specimens exhibited no apparent fatigue cracking even though the applied stress was equal to the peak stress that caused fatigue in notched specimens. Differences in fatigue life between the notch designs A and B suggest that the lower the value of the $(D/d)^2K_T$ term the greater the fatigue life.

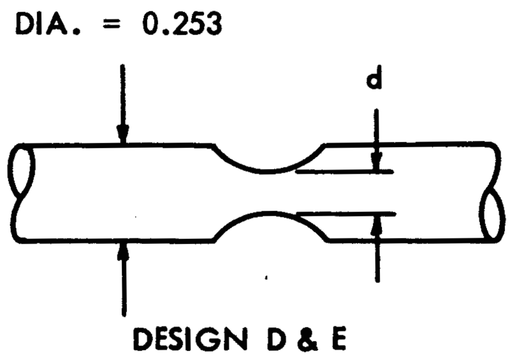
A fatigue specimen of TZC was metallographically examined to determine the morphology of the fatigue crack. The surface of the specimen at the base of the notch in the vicinity of the fatigue crack is shown in Figure 11. At 250X a number of surface ruptures surround the principal crack. A low magnification view of the cross section of the entire crack, shown in Figure 12, reveals an apparent substructure adjacent to the fissure. An electron micrograph at 6000X, Figure 13, shows the development of a well defined, very fine structure along the crack path which indicates that the effect is real and not a strain artifact.

The material adjacent to the crack had a hardness of 296 DPH compared to 234 DPH just outside of this zone. At present no satisfactory explanation is available to account for the development of the substructure along the crack path. Additional specimens are being examined to determine the generality of this observation.

On the basis of the Goodman diagram obtained for notch specimens of TZC, an "A" ratio of approximately 0.20 was selected as a test condition in which sufficient dynamic stress could be developed to produce fatigue failure in a smooth specimen. The test was conducted at 2000°F (1093°C) at a static stress of 20 Ksi ($1.38 \times 10^8 N/m^2$) and a dynamic stress of 3.94 Ksi ($2.72 \times 10^7 N/m^2$). Under these conditions the smooth 1/4" diameter TZC specimen (Heat M-88) annealed at 3092°F (1700°C) failed in 37.2 hours (2.57×10^9 cycles). This result is in excellent agreement with the predictions obtained from the Goodman diagram shown in Figure 8.

* G. D. McArdle, R. Q. Barr, and M. Semchyshen, "Investigation of Molybdenum- and Tungsten-Base Alloy Sheet Materials", Climax Molybdenum Co. Final Report Contract NOW 61-0581-d, (January 15, 1963).





	MINOR DIAMETER (IN.) d	NOTCH RADIUS (IN.) R	THEORETICAL STRESS CONCENTRATION FACTOR K_T
A	0.174	0.032	3.93
B	0.228	0.032	2.25
C	0.196	0.031	3.17
D	0.174	0.253	2.41
E	0.228	0.253	1.44

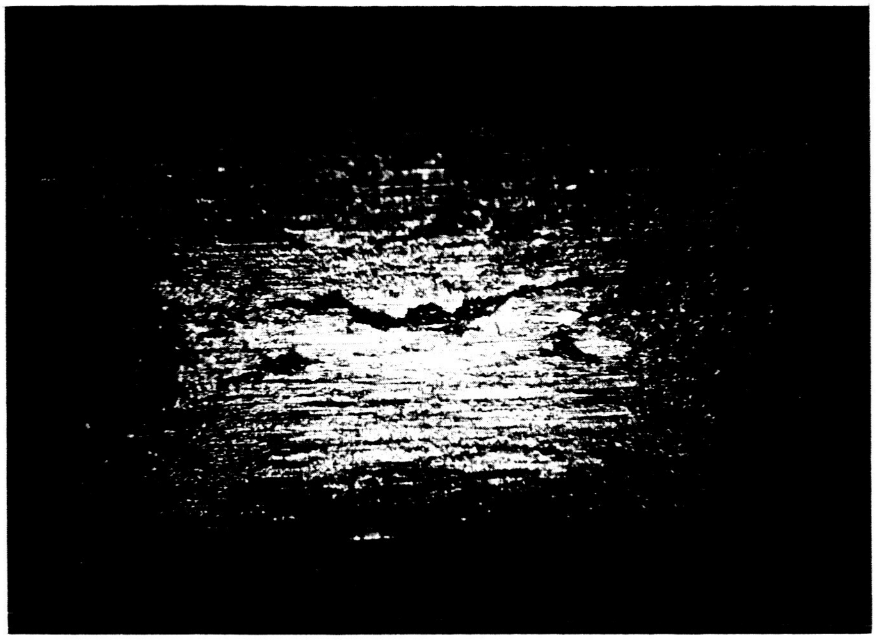
FIGURE 10 DESIGN OF NOTCH CONFIGURATIONS USED FOR NOTCH EVALUATION STUDIES

TABLE V

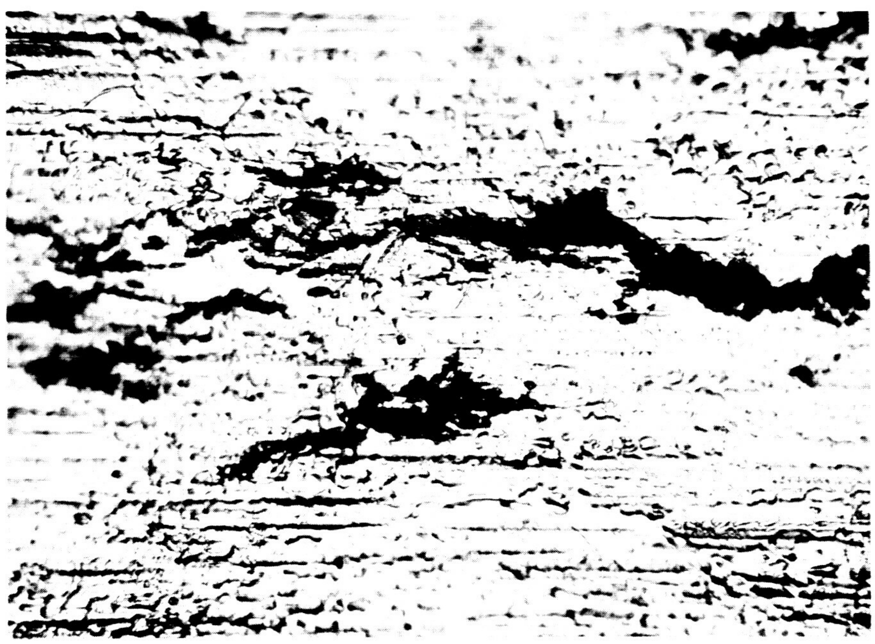
Summary of Notched Fatigue Tests With Various Notch Configurations Using Specimens of TZM (Heat 7468)
Recrystallized One Hour at 2850°F (1566°C), Ambient Temperature 2000°F (1093°C), Vacuum Environment < 1 x 10^{-7} Torr

Specimen	Notch* Design	$(\frac{D}{d})^2 K_T$	Peak Total Stress Ksi (6.89 x 10^6 N/m^2)	Static Stress Ksi (6.89 x 10^6 N/m^2)	Failure Time-Hrs.	Cycles to Failure	Temperature Increase °F
50	A	3.93	8.24	1.33	~ 0.15	1.0 x 10^7	-
51	A	3.93	7.81	1.33	7.6	5.3 x 10^8	11
53	Smooth	1.00	8.54	0.34	>357	> 2.5 x 10^{10}	111
53	Smooth	1.00	8.43	0.34	>32.6	> 2.3 x 10^9	157
54	B	2.25	12.70	0.76	>16.9	> 1.2 x 10^9	26
54	B	2.25	16.70	0.76	1.60	1.1 x 10^8	36
55	B	2.25	14.71	0.76	1.37	9.6 x 10^7	58

* See Figure 10 for notch design



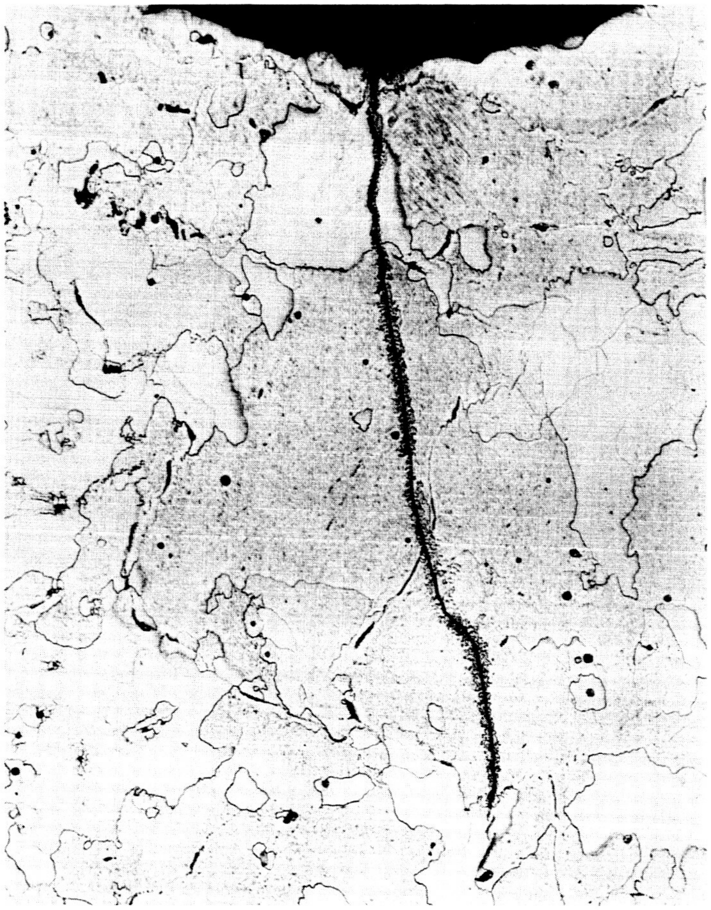
100X



250X

FIGURE 11 FATIGUE CRACKS AT BASE OF NOTCH SPECIMEN NO. 24, TZC (M-91) ANNEALED AT 3092°F (1700°C) FOR 1 HOUR. UNETCHED.

2253A



SPEC. #24 100X

FIGURE 12 APPEARANCE OF FATIGUE CRACK IN TZC SPECIMEN, ANNEALED 3092°F (1700°C), 1 HOUR. TESTED AT AN AMBIENT TEMPERATURE OF 2000°F (1093°F) FOR 4.7 x 10^9 CYCLES, MURAKAMI'S ETCH

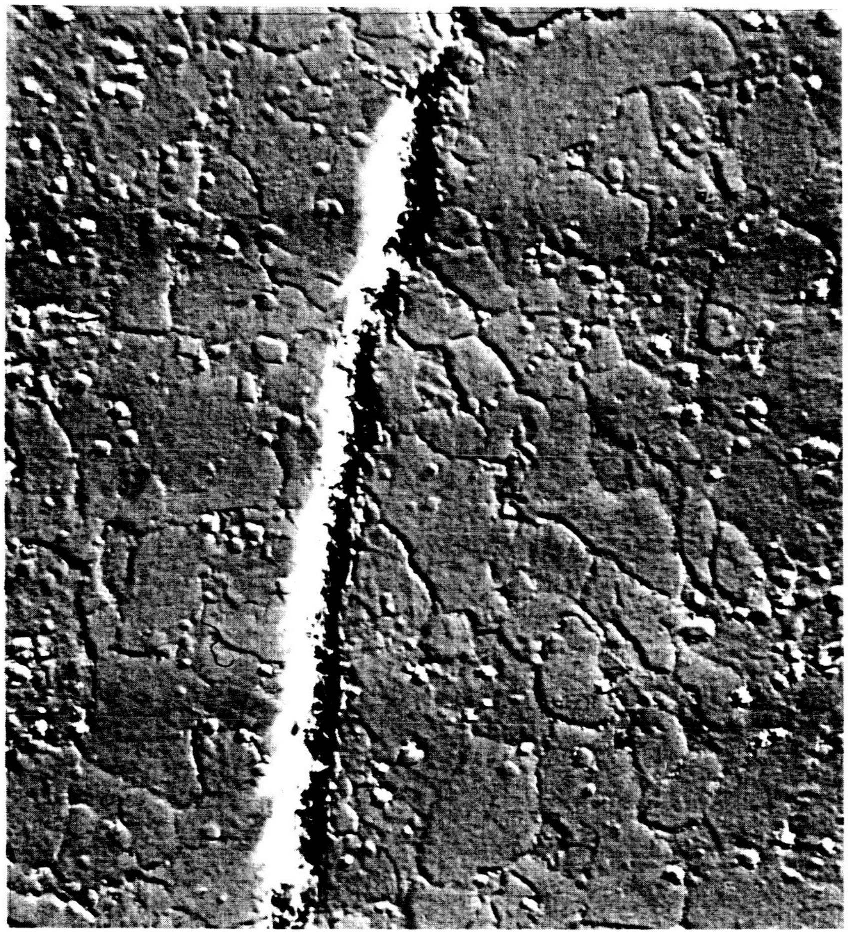


FIGURE 13 ELECTRON MICROGRAPH OF FATIGUE CRACK IN SPECIMEN #24

A second test is being conducted with TZC bar stock (Heat 4320-2) annealed at 3092°F (1700°C) at an ambient temperature of 2000°F (1093°C), a static stress of 20 Ksi ($1.38 \times 10^8 N/m^2$), and a dynamic stress of 4.2 Ksi ($2.76 \times 10^7 N/m^2$). No fatigue failure has occurred in this material after 470 hours.

By measuring the change in length between the shoulders of the specimen, the creep of the smooth TZC specimens during fatigue testing could be observed. The first fatigue test specimen exhibited 0.1% creep after 37 hours at 2000°F (1093°C), a static load of 20 Ksi ($1.38 \times 10^8 N/m^2$) and an "A" ratio of 0.20. This value was a factor of two greater than the creep obtained on specimens without the superposition of a dynamic stress. The second test of the specimen from the bar stock has allowed the creep to be observed in greater detail. Creep extensions after 470 hours of testing under a combined static and dynamic load are given in Table VI and Figure 14, along with creep data for TZC from Heats M-80 and M-91. A rapid increase in the length occurs during the first 1 to 2 hours resulting in part from the increased temperature due to self-heating. The creep rate after this initial increase is comparable to that obtained in specimens where no superimposed dynamic stress is present.

IV FUTURE WORK

Tests with specimens of varying notch geometries will be conducted at 2000°F (1093°C) ($A = \infty$) to determine contribution of stress concentration factor on the high frequency, elevated temperature fatigue properties. Tests will be continued with TZC to determine the fatigue strength of smooth specimens at relatively low A ratios. Additional metallographic examination will be performed in an attempt to further define the significance of the substructure present in the TZC alloy along the fatigue crack path.

TABLE VI

Creep data TZC Bar (Heat 4230-2) Annealed 3092°F (1700°C), For One Hour Tested at 2000°F (1093°C), 20 Ksi ($1.38 \times 10^8 N/m^2$) Static Stress, 4.2 Ksi ($2.9 \times 10^7 N/m^2$) Dynamic Stress, and 20 kHz, in Vacuum Environment $<1 \times 10^{-7}$ Torr

Time (Hrs.)	Length Change inches (1" G. L.)	Creep (%)	Pressure (Torr)
0	0.0000	0	2×10^{-7}
0.1	0.0012	0.12	1×10^{-7}
1.4	0.0020	0.20	5×10^{-8}
18.0	0.0016	0.16	1.7×10^{-8}
110.1	0.0022	0.22	9.6×10^{-9}
134.2	0.0026	0.26	9.5×10^{-9}
158.4	0.0024	0.24	8.1×10^{-9}
182.0	0.0022	0.22	8.5×10^{-9}
253.5	0.0024	0.24	7.8×10^{-9}
278.1	0.0025	0.25	6.6×10^{-9}
304.7	0.0022	0.22	7.2×10^{-9}
326.5	0.0026	0.26	7.3×10^{-9}
350.2	0.0027	0.27	6.7×10^{-9}
422.3	0.0027	0.27	7.0×10^{-9}
446.6	0.0029	0.29	6.7×10^{-9}
470.0	0.0032	0.32	6.3×10^{-9}

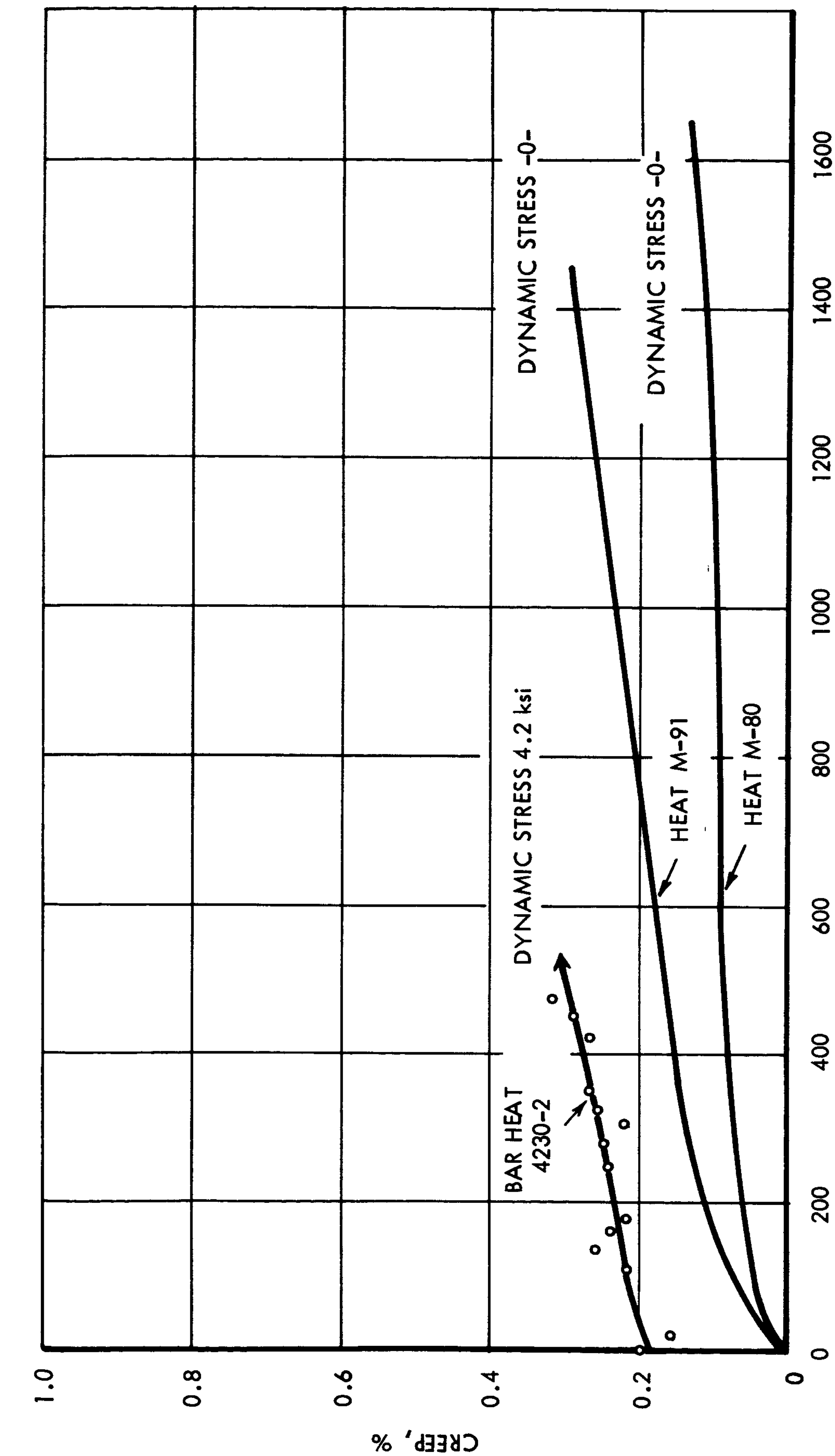


FIGURE 14 CREEP DATA, TZC, ANNEALED 3092°F (1700°C), 1 HOUR. TESTED AT 2000°F (1093°C) AND 20 ksi (1.38×10^8 N/m^2) STATIC STRESS IN VACUUM ENVIRONMENT $< 1 \times 10^{-7}$ TORR.